



# Assessing the environmental impact of energy production from hydrochar generated via hydrothermal carbonization of food wastes



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## ABSTRACT

Although there are numerous studies suggesting hydrothermal carbonization is an environmentally advantageous process for transformation of wastes to value-added products, a systems level evaluation of the environmental impacts associated with hydrothermal carbonization and subsequent hydrochar combustion has not been conducted. The specific objectives of this work are to use a life cycle assessment approach to evaluate the environmental impacts associated with the HTC of food wastes and the subsequent combustion of the generated solid product (hydrochar) for energy production, and to understand how parameters and/or components associated with food waste carbonization and subsequent hydrochar combustion influence system environmental impact. Results from this analysis indicate that HTC process water emissions and hydrochar combustion most significantly influence system environmental impact, with a net negative GWP impact resulting for all evaluated substituted energy-sources except biomass. These results illustrate the importance of electricity production from hydrochar particularly when it is used to offset coal-based energy sources. HTC process water emissions result in a net impact to the environment, indicating a need for developing appropriate management strategies. Results from this analysis also highlight a need for additional exploration of liquid and gas-phase composition, a better understanding of how changes in carbonization conditions (e.g., reaction time and temperature) influence metal and nutrient fate, and the exploration of liquid-phase treatment.

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## 1. Introduction

Hydrothermal carbonization (HTC) is a relatively low temperature thermal conversion process that is gaining significant attention as a sustainable and environmentally beneficial approach for the conversion of biomass and waste streams to value-added products (e.g., Berge et al., 2011; Hwang et al., 2012; Li et al., 2013; Libra et al., 2011; Román et al., 2013; Titirici et al., 2012; Sevilla and Fuertes, 2009). HTC is a unique process in which wet feedstocks are thermally converted at relatively low temperatures (<350 °C) and with relatively low input energy requirements (Funke and Ziegler, 2010; Libra et al., 2011; Titirici et al., 2012). As a result of this process, a carbon-rich and energy-dense solid material is formed. This solid product, often referred to as hydrochar, has garnered considerable study, as its properties make it amenable for use in a variety of environmentally-relevant applications, including as a soil amendment, energy source,

environmental sorbent, and/or a material for energy and/or hydrogen storage (Libra et al., 2011; Kammann et al., 2012; Berge et al., 2011; Flora et al., 2013; Heilmann et al., 2010; Kumar et al., 2011; Sevilla et al., 2011).

The many potential environmental benefits associated with HTC have led to the recent exploration of using this process as a means to convert components of municipal solid waste (MSW) to a solid fuel source (e.g., Berge et al., 2011; Funke and Ziegler, 2010; Kaushik et al., 2014; Libra et al., 2011; Phuong et al., 2015; Ramke et al., 2009). Results from several studies indicate that hydrochar generated from the conversion of different municipal waste materials has an energy density equivalent to that of coal (e.g., Berge et al., 2011; Hwang et al., 2010; Kaushik et al., 2014; Li et al., 2013; Phuong et al., 2015). Studies have also identified potential environmental benefits associated with using HTC in this manner, such as a reduction in greenhouse gas emissions and lower energy requirements for the conversion of wet feedstocks when compared to more traditional waste conversion processes (Titirici et al., 2007; Ramke et al., 2009; Falco et al., 2011; Funke and Ziegler, 2010; Román et al., 2013).

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Although there are numerous studies suggesting hydrothermal carbonization is an environmentally advantageous process, a systems level evaluation of the environmental impacts associated with hydrothermal carbonization and subsequent hydrochar combustion has not been conducted. Such an analysis is needed to more objectively identify and quantify environmental advantages. Because using hydrothermal carbonization in this manner is in its infancy, a major obstacle associated with conducting such a comprehensive analysis of HTC is a lack of relevant data. There are many unknowns associated with carbonization, particularly with respect to process scale-up. This lack of data limits the ability to conduct a fair process comparison with other well-established processes (e.g., incineration, composting, etc.) for which such data exist (e.g., Boldrin et al., 2010; Chen and Christensen, 2010; Riber et al., 2008; Turconi et al., 2011). A systems level analysis, however, can be used to provide an understanding of how parameters and/or components associated with feedstock carbonization and/or subsequent hydrochar combustion (e.g., fate of metals and nutrients, etc.) influence system environmental impact. Understanding such relationships is critical in identifying and prioritizing research needs and data gaps.

The purpose of this work is to use a systems level analysis to understand how different factors/components associated with the HTC process influence the environmental impacts of hydrochar production and subsequent combustion for energy generation from the carbonization of food waste. Because food waste is a wet feedstock, it is better suited for hydrothermal carbonization than more traditional dry carbonization processes (e.g., pyrolysis). Accordingly, several studies evaluating the hydrothermal carbonization of food wastes for various purposes have been conducted (e.g., Kaushik et al., 2014; Li et al., 2013; Parshetti et al., 2014). Significant experimental efforts associated with the carbonization of food waste collected from restaurants located in the United States have been previously conducted (Li et al., 2013) and results from these efforts indicate that hydrochar energy contents are significant and that food waste carbonization followed by hydrochar combustion results in a net energy savings (Li et al., 2013). The specific objectives of this work are to: (1) evaluate the environmental impact of the HTC of food wastes and the subsequent combustion of the solid product (e.g., hydrochar) for energy production using life cycle assessment (LCA) to identify the most impactful processes and (2) understand how parameters and/or components associated with food waste carbonization and/or subsequent hydrochar combustion (e.g., fate of metals, fate of nutrients, electricity needs) influence system environmental impact.

## 2. Materials and methods

### 2.1. Food waste carbonization

Results from previously conducted food waste carbonization experiments were used in this modeling effort (Li et al., 2013). As described in Li et al. (2013), food waste was periodically collected from restaurants located near the University of South Carolina (Columbia, SC, USA). Visual observation of the collected food indicated the waste consisted of a variety of cooked foods (e.g., meat, seafood, French fries, vegetables), uncooked foods (e.g., vegetables, seafood) and condiments (e.g., salad dressing, ketchup, cocktail sauce). Because of processing limitations, food containing bones (e.g., chicken bones) was not used in these experiments. The packaging materials found in this waste consisted of paper, plastics, and cardboard. The elemental composition of these wastes is presented in Table 1.

**Table 1**  
Feedstock properties.

Elements	Food waste	Components of packaging waste		
		Paper	Cardboard	Plastic
Al (%TS) <sup>a</sup>	0.0222	0.100	0.350	0.00730
As (%TS) <sup>a</sup>	2.63E–05	1.02E–05	1.02E–05	1.00E–05
Ash (%TS) <sup>a</sup>	5.20	9.56	5.15	4.62
C bio (%TS) <sup>b,c</sup>	52.4	40.6	40.0	0
C fossil (%TS) <sup>b,c</sup>	0	0	0	62.0
Ca (%TS) <sup>a</sup>	0.516	0.873	1.59	1.55
Cd (%TS) <sup>a</sup>	2.63E–05	1.02E–05	1.02E–05	1.00E–05
Cr (%TS) <sup>a</sup>	5.27E–05	0.000418	0.000194	0.00048
Cu (%TS) <sup>a</sup>	0.000421	0.00286	0.000153	0.0007
Energy (MJ/kgTS) <sup>b</sup>	22.0	15.7	13.0	25.5
Fe (%TS) <sup>a</sup>	0.00632	0.0171	0.0152	0.00901
H (%TS) <sup>a</sup>	8.30	6.43	5.95	4.75
Hg (%TS) <sup>a</sup>	1.32E–06	8.16E–07	5.11E–07	5.00E–07
K (%TS) <sup>a</sup>	0.578	0.0135	0.00572	0.00891
Mg (%TS) <sup>a</sup>	0.0602	0.0463	0.0357	0.0314
Mn (%TS) <sup>a</sup>	0.00961	0.000479	0.000286	0.00021
N (%TS) <sup>b</sup>	2.80	0.08	0.13	0.10
Na (%TS) <sup>a</sup>	0.890	0.0920	0.0563	0.0412
Ni (%TS) <sup>a</sup>	5.27E–05	0.000479	0.000204	0.00044
P (%TS) <sup>a</sup>	0.287	0.00510	0.00317	0.00370
Pb (%TS) <sup>a</sup>	5.27E–05	5.10E–05	3.06E–05	2.00E–05
S (%TS) <sup>a</sup>	0.177	0.0220	0.0185	0.00400
Se (%TS) <sup>a</sup>	5.27E–05	2.04E–05	2.04E–05	2.00E–05
Sr (%TS) <sup>a</sup>	0.00121	0.00133	0.000980	0.000901
Ti (%TS) <sup>a</sup>	0.000711	0.265	0.00592	0.0655
TS (% <sup>b</sup> )	38.0	53.7	62.8	94.1
VS (%TS) <sup>a</sup>	94.8	90.4	94.9	95.4
Water (% <sup>b</sup> )	62.0	46.3	37.2	5.87
Zn (%TS) <sup>a</sup>	0.00231	0.000581	0.000204	0.00650

<sup>a</sup> Parameters were measured by Huffman Laboratories, Inc.

<sup>b</sup> Parameters were measured as described in Li et al. (2013).

<sup>c</sup> Carbon in the food, paper, and cardboard fractions are considered biogenic; carbon associated with the plastic material is of fossil origin.

Experiments investigating carbonization of the separated food waste over a range of temperatures, reaction times, and initial solids concentrations were conducted. Experiments containing food and various percentages of packaging materials were also conducted to evaluate the influence of packaging on food waste carbonization. Specific details associated with the carbonization experiments can be found in Li et al. (2013). A summary of the results from these carbonization experiments that were used in this modeling effort is included Tables 2–4.

### 2.2. Modeling approach

LCA modeling was performed using the Environmental Assessment System for Environmental Technologies (EASETECH, version 2.0.0), a mass-flow based LCA tool developed by researchers at the Technical University of Denmark to evaluate the environmental impact of waste management processes (Clavreul et al., 2014). This specific tool was chosen for use in this study because it is designed to calculate and track waste flows, resource consumption and recovery, and environmental emissions through user-defined waste management systems. All input waste material fractions are specified in terms of elemental composition (e.g., carbon, hydrogen, etc.) and fraction-specific properties (e.g., moisture and energy content, etc.), and are tracked through the system. Waste management processes are modeled in EASETECH by assembling a series of default template processes, such as substance transfer and emissions to the environment, as described in more detail by Clavreul et al. (2014). Each template process is subsequently populated with user provided process input/output information. Additional details associated with EASETECH and its use in modeling various waste management systems can be found

**Table 2**  
Carbonization experiment results used in this study (Li et al., 2013).

Feedstock carbonized	Reaction conditions		Solids				Liquid				Gas (g/g dry initial feedstock)							
	Temp (°C)	Time (h)	Initial solids		Yield (% dry char)	Energy content (J/g dry char)	C (% dry char)	H (% dry char)	N (% dry char)	COD (mg/L)	BOD (mg/L) <sup>a</sup>	pH	CO <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>3</sub> H <sub>8</sub>	C <sub>4</sub> H <sub>10</sub>	C <sub>5</sub> H <sub>12</sub>
			Food waste (% dry)	Packaging (% wet)														
Food	225	16	32	0	69.57	28,187	64.87	7.88	3.18	68700	34,912	4.60	0.102	8.20E-05	5.08E-05	5.59E-05	5.54E-05	4.54E-05
	250	16	32	0	74.06	30,089	67.88	7.48	3.51	70,320	28,539	4.86	0.109	1.85E-04	1.31E-04	1.32E-04	8.67E-05	nd
	275	4	32	0	66.45	29,743	68.94	7.75	3.46	64,750	50,243	4.66	0.099	1.56E-04	1.13E-04	1.18E-04	8.74E-05	7.43E-05
Food and packaging	275	16	32	0	63.73	31,538	71.91	8.16	3.23	63,820	24,474	5.00	0.117	3.33E-04	2.94E-04	3.04E-04	2.02E-04	1.31E-04
	275	96	32	0	57.87	34,791	75.23	8.67	3.22	48,480	24,474	5.59	0.120	7.26E-04	8.27E-04	9.17E-04	5.01E-04	2.26E-04
	250	16	30	10	68.31	27,352	68.95	7.97	3.34	98,640	53,289	4.87	0.096	1.23E-04	8.09E-05	8.52E-05	7.24E-05	5.63E-05
	250	16	20	40	66.61	24,078	64.53	6.47	1.67	na	na	na	0.102	1.62E-04	9.20E-05	8.43E-05	6.15E-05	5.48E-05

na = not applicable (no liquid drained); nd = not detected.

<sup>a</sup> BOD concentrations are reflective of the average of process waters from a range of times: early (0.5–8 h) or late (16–96 h) at each reaction temperature.

elsewhere (e.g., Clavreul et al., 2014; Jain et al., 2014; Starostina et al., 2014; Yang et al., 2014).

The process flow diagram associated with the system modeled in this study is provided in Fig. 1. This diagram illustrates the general process of electricity production from combustion of the hydrochar generated from the hydrothermal carbonization of food waste. The processes involved are classified into two major categories: (1) hydrothermal carbonization (e.g., waste conversion to solid, liquid, and gas) and (2) electricity generation from the hydrochar (e.g., preprocessing and hydrochar combustion). The functional unit used in this study is the treatment of 1 kg of food waste previously sorted from the waste stream. The mass of sorted waste consists of either pure food waste (assuming all packaging materials have been removed during sorting) or food with associated packaging materials (e.g., paper, cardboard, and plastic wrapping). The sorting of this waste occurs upstream of the modeled system, and may have been performed by consumers at homes or at a materials recovery facility (MRF) following waste collection. Upstream processes, such as waste sorting, collection and transport are not included in this analysis because the objective of this work is to isolate and understand how different factors influence the environmental impact of the carbonization and subsequent hydrochar combustion processes. Emissions associated with these upstream processes will ultimately influence system environmental impact (e.g., greenhouse gas emissions); the specific contribution of these processes depends on site-specific factors, such as transportation distances and sorting technologies (Laurent et al., 2014). As described previously, the initial properties associated with the input food waste and individual packaging materials are included in Table 1 and were either derived from Li et al. (2013) or, using the same food waste source, measured (Huffman Laboratories, Inc.).

2.2.1. HTC LCA model

Fig. 1 illustrates how hydrothermal carbonization is modeled using EASETECH. The first stage of the carbonization framework is process heating (e.g., solids and liquid). Energy requirements were calculated based on feedstock solids and moisture contents. The energy required to heat the water for carbonization was calculated by accounting for the mass distribution of water at the target temperature and by evaluating the enthalpy difference of the system at the final and initial temperatures (following procedures outlined by Berge et al. (2011), Li et al. (2013)). These values depend on both reaction temperature and the mass of water present. The energy required to heat the solids was calculated using specific heat capacities for food and the packaging materials, as outlined in Li et al. (2013). The required energies were used to determine electricity requirements (kWh), initially assuming a perfectly insulated process. The type of electrical energy and associated emissions with this process were modeled using average US electricity (at the grid) information (NREL, 2012).

The second component associated with the hydrothermal carbonization framework is waste conversion and subsequent generation of the solid, liquid, and gas products (Fig. 1). This process is modeled using mass distribution coefficients to distribute specific elements (e.g., carbon, energy) of the input stream to the liquid, solid and gaseous products. If possible, mass distribution coefficients were calculated from experimental data (Tables 2 and 3). If unavailable, data from the literature were compiled and used to assign the necessary mass distribution coefficients, as documented in Table 4. For the purposes of this study, it is assumed that the resulting liquid (emitted to surface water) and gas streams are emitted without treatment (Fig. 1).

It is important to note that other specific process variables/requirements (e.g., chemicals, oil, equipment, etc.) during carbonization are currently unknown and thus not included in this

**Table 3**  
Summary of data associated with gravity drainage of the recovered solids (Li et al., 2013).

Feedstock	Reaction conditions			Moisture drained (% of initially present moisture)	Moisture remaining in char (% of initially present moisture)	Moisture content of solids following gravity drainage (% wet wt.)
	Temp (°C)	Time (h)	% Packaging			
Food	225	16	0	23	77	72
	250	16	0	61	39	55
	275	4	0	45	55	66
	275	16	0	61	39	58
	275	96	0	84	16	37
Food and packing	250	16	7	38	62	63
	250	16	27	0	100	66

model. Information associated with these process components is ultimately necessary to better understand the impact of carbonization and can be added as such information becomes available.

### 2.2.2. Hydrochar combustion LCA model

Energy can be produced from combustion of the hydrochar. The specific energy content values of the generated hydrochar are included in Table 2. This process, along with the required preprocessing of the hydrochar, is modeled as a three-stage process (Fig. 1). The first stage of this process is separation of the solids and liquid generated from the carbonization process (stage 3 in Fig. 1). It is assumed that following carbonization, a portion of the process water will be removed from the material via gravity drainage (Fig. 1), a process requiring no energy input and yielding no environmental emissions. Data associated with the dewaterability of the generated solids under gravity are available from previously conducted experiments (Li et al., 2013), and are summarized in Table 3. For the purposes of this study, the drained liquid is emitted without treatment to surface water (stage 3, see Fig. 1).

The next stage is solids drying (stage 4, Fig. 1). The mass of water remaining in the hydrochar following gravity drainage requires evaporation prior to combustion (Table 3). The drying energy was determined assuming that the water is evaporated at a temperature of 100 °C. The mass of water remaining in the solids following drainage was calculated based on the experimental results described in Li et al. (2013), as summarized in Table 3. These values depend on initial carbonization conditions, including initial feedstock moisture and solids contents, reaction time, and reaction temperature. The required energies were used to determine electricity requirements (kW h), initially assuming a perfectly insulated process. As described previously, the source of electrical energy and associated emissions are modeled using average US electricity information (NREL, 2012).

The last stage of this process is hydrochar combustion (step 5, Fig. 1). Once dried, it is assumed the hydrochar is combusted and the heat generated is ultimately converted to electricity. The energy required to heat the solids to the combustion temperature (1100 °C) was calculated using an assumed specific heat capacity of the hydrochar (see Li et al., 2013) and subsequently used to determine electricity requirements (assuming a perfectly insulated process). Electricity generated from hydrochar combustion is used to offset electricity generated via other energy sources, with environmental credits given for these offsets. Because hydrochar has been defined as a coal-like material, it is likely that generated hydrochar will be transported and ultimately combusted in coal-fired power plants, ultimately substituting coal-derived electricity. Assuming the modeled scenarios occur in the short-term and the energy-recovery infrastructure in the US remains the same, this represents the most likely scenario for electricity generation via hydrochar combustion. It should also be noted that simulations evaluating the influence of substituting electricity generation via

hydrochar for different source of energy were conducted (Table 6). The energy sources evaluated include: different types of coal (e.g., lignite, anthracite, bituminous), biomass, and the average US electricity mix. In all simulations, it is assumed that electrical energy is generated and/or consumed because this is representative of conditions found in the US.

Because of a lack of data associated with emissions from hydrochar combustion, as well as the distribution of elements during hydrochar combustion, hydrochar combustion is assumed to mimic that of MSW incineration. The default waste incineration process provided in EASETECH was used to model hydrochar combustion. This default module uses predetermined distribution coefficients to distribute elements to the air, ash, and water phases (Riber et al., 2008). This module also includes emissions associated with the production and consumption of other process needs, such as activated carbon used for gas cleaning. Emissions associated with the incineration process (e.g., not dependent on the input waste material, such as dioxin) are also included. Additional details associated with the incineration module, including transfer coefficients, can be found elsewhere (Riber et al., 2008). Two changes to this module were made: (1) district heating was removed because this is not a common practice in the US and (2) the type of electrical energy and associated emissions was modeled using average US electricity information (NREL, 2012).

### 2.3. Life cycle inventory data

Inventory data associated with the carbonization of food waste and subsequent combustion of the hydrochar for electricity generation were either calculated from experimental results or collected from the literature, as described in Tables 2–4. There is a significant amount of uncertainty associated with the fate of elements (e.g., metals, nutrients) during carbonization. Therefore, several model simulations were conducted to evaluate how changes in the fate of different elements during the carbonization and hydrochar combustion processes influence system environmental impact. These data were taken from that found in the literature and provided in Table 4.

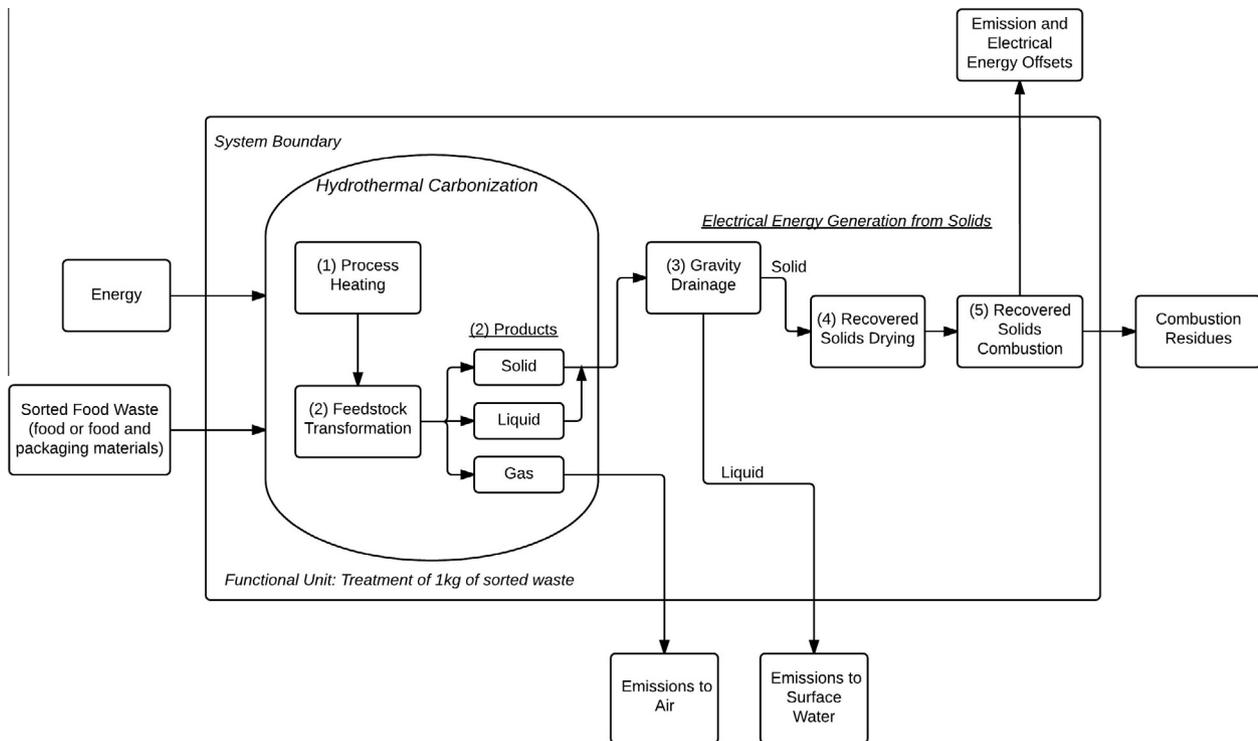
### 2.4. Life cycle impact assessment

Nine of the International Reference Life Cycle Data System (ILCD)-recommended impact categories were evaluated and compared in this work (Table 5); each method is described in Hauschild et al. (2012). These categories include: global warming potential (GWP), acidification (AP), terrestrial eutrophication (TEP), human toxicity (cancer, HT-C, and non-cancer effects, HT-NC), photochemical oxidant formation (POF), marine eutrophication (MEP), freshwater eutrophication (FEP), and ecotoxicity (ET). Normalization or weighting of the impacts was not performed in this study.

**Table 4**  
Life cycle inventory data.

System Step	Parameter	Base Case Values	Range Evaluated	Data Source
1	Electricity Requirements (kWh/g dry feedstock)	0.000956	0.0008 - 0.002	Calculated as described by Li et al. (2013)
	Electricity Source	US Grid	-	NREL (2012)
2: Waste Conversion	Reaction Temperature (°C)	275	225 - 275	Experiments conducted by Li et al. (2013)
	Reaction Time (hours)	16	0.5 - 96	Experiments conducted by Li et al. (2013)
	Packaging Material (%)	0	0 - 40	Experiments conducted by Li et al. (2013)
	Solids Yield (% dry wt.)	63.7	63.7 - 75	Experiments conducted by Li et al. (2013)
	VS (% dry wt.)	61.3	61.3 - 72	Experiments conducted by Li et al. (2013)
	Energy Distribution (%)	Solid: 86.63	Solid: 82 - 99	Experiments conducted by Li et al. (2013)
		Liquid: 13.11	Liquid: 0.2 - 13.11	
		Gas: 0.26	Gas: 0.11 - 0.38	
	Moisture Distribution (%)	Solid: 40	Solid: 15 - 100	Experiments conducted by Li et al. (2013)
		Liquid: 60	Liquid: 0 - 85	
	Carbon, biogenic origin (%)	Solid: 84.2	Solid: 80 - 86	Experiments conducted by Li et al. (2013)
		Liquid: 9.7	Liquid: 0 - 13	
		Gas: 6.1	Gas: 5 - 8	
	Carbon, fossil derived (%)	Solid: 0	Solid: 0 - 100	Experiments conducted by Li et al. (2013)
		Liquid: 0	Liquid: 0	
		Gas: 0	Gas: 0	
	Ash (%)	100% remains in solid	100% remains in solid	Experiments conducted by Li et al. (2013)
	Hydrogen (%)	Solid: 63	Solid: 60 - 70	Experiments conducted by Li et al. (2013)
		Liquid: 27	Liquid: 0 - 100	
	Nitrogen (%)	Gas: 0	Gas: 0 - 100	Average of values taken from Reza et al. (2013)
		Solid: 61.5	Solid: 0 - 100	
		Liquid: 38.5	Liquid: 0 - 100	
	Al (%)	Solid: 68	Solid: 0 - 100	Average of values taken from Reza et al. (2013)
		Liquid: 32	Liquid: 0 - 100	
	As (%)			Calculated from mass balances
	Ca (%)	Solid: 50.5	Solid: 0 - 100	Average of values taken from Reza et al. (2013) and Escala et al. (2013)
		Liquid: 49.5	Liquid: 0 - 100	
	Cd (%)	Solid: 53.5	Solid: 0 - 100	Average of values taken from Reza et al. (2013)
		Liquid: 46.5	Liquid: 0 - 100	
	Cr (%)	Solid: 32	Solid: 0 - 100	Average of values taken from Reza et al. (2013)
		Liquid: 68	Liquid: 0 - 100	
	Cu (%)	Solid: 81.5	Solid: 0 - 100	Average of values taken from Reza et al. (2013) and Escala et al. (2013)
		Liquid: 18.5	Liquid: 0 - 100	
	Fe (%)	Solid: 45	Solid: 0 - 100	Average of values taken from Reza et al. (2013)
		Liquid: 55	Liquid: 0 - 100	
		Solid: 95	Solid: 0 - 100	
	Hg (%)	Liquid: 5	Liquid: 0 - 100	Average of values taken from Escala et al. (2013)
		Gas: 0	Gas: 0 - 100	
		Solid: 48	Solid: 0 - 100	
	Mg (%)	Liquid: 52	Liquid: 0 - 100	Average of values taken from Reza et al. (2013)
		Solid: 20	Solid: 0 - 100	
	Mn (%)	Liquid: 80	Liquid: 0 - 100	Average of values taken from Reza et al. (2013) and Escala et al. (2013)
		Solid: 41.5	Solid: 0 - 100	
	Na (%)	Liquid: 58.5	Liquid: 0 - 100	Average of values taken from Reza et al. (2013)
		Solid: 78.5	Solid: 0 - 100	
	Ni (%)	Liquid: 21.5	Liquid: 0 - 100	Average of values taken from Reza et al. (2013)
		Solid: 93.5	Solid: 0 - 100	
Pb (%)	Liquid: 6.5	Liquid: 0 - 100	Average of values taken from Reza et al. (2013)	
	Solid: 100	Solid: 0 - 100		
Se (%)	Liquid: 0	Liquid: 0 - 100	Distribution was assumed	
	Solid: 100	Solid: 0 - 100		
Sr (%)	Liquid: 0	Liquid: 0 - 100	Distribution was assumed	
	Solid: 100	Solid: 0 - 100		
Ti (%)	Liquid: 0	Liquid: 0 - 100	Distribution was assumed	
	Solid: 66	Solid: 0 - 100		
Zn (%)	Liquid: 34	Liquid: 0 - 100	Average of values taken from Reza et al. (2013) and Escala et al. (2013)	
	Solid: 51.5	Solid: 0 - 100		
P (%)	Liquid: 48.5	Liquid: 0 - 100	Average of values taken from Reza et al. (2013) and Escala et al. (2013)	
	Solid: 46.5	Solid: 0 - 100		
S (%)	Liquid: 53.5	Liquid: 0 - 100	Average of values taken from Reza et al. (2013) and Escala et al. (2013)	
	Solid: 19	Solid: 0 - 100		
K (%)	Liquid: 81	Liquid: 0 - 100	Average of values taken from Reza et al. (2013)	
	Solid: 19	Solid: 0 - 100		
2: Gas Emissions	Carbon Dioxide (g/g initial TS)	0.117	0.096 - 0.120	Experiments conducted by Li et al. (2013)
	Butane (g/g initial TS)	$2.02 \times 10^{-4}$	$5.54 \times 10^{-5}$ to $5.01 \times 10^{-4}$	
	Methane (g/g initial TS)	$3.33 \times 10^{-4}$	$8.20 \times 10^{-5}$ to $7.26 \times 10^{-4}$	
	Ethane (g/g initial TS)	$2.94 \times 10^{-4}$	$5.08 \times 10^{-5}$ to $8.27 \times 10^{-4}$	
	Propane (g/g initial TS)	$3.04 \times 10^{-4}$	$5.59 \times 10^{-5}$ to $9.17 \times 10^{-4}$	
	Pentane (g/g initial TS)	$1.31 \times 10^{-4}$	0 to $2.26 \times 10^{-4}$	
2: Liquid Emissions	S	All S is converted to sulfate		Data assumed
	P	All P is converted to phosphate		Data assumed
	N	98.2% of N is converted to ammonium		Average values from: Du et al., (2012); Escala et al. (2013); Heilmann et al. (2011)
		1.8% of N is converted to nitrate 0.016% of N is converted to nitrite		
	Metals	All metals in liquid are in present in their ionic form		Data assumed
	COD and BOD	All COD and BOD is emitted		Experiments conducted by Li et al. (2013)
4: Recovered Solids Drying and 5: Recovered Solids Combustion	Electricity Requirements (kWh/g dry feedstock)	0.00092	0.0009 - 0.002	Calculated as described by Li et al., (2013)
	Electricity Source	US Grid	-	NREL (2012)
Efficiency of Electricity Generation form	Hydrochar	0.3	0.1 - 0.5	Data assumed
	Substitution Energy Source	Lignite Coal	Bituminous and Anthracite Coal; Biomass; Avg. US Mix	Data associated with each coal and the biomass was taken from NREL (2012)

(See above-mentioned references for further information.)



**Fig. 1.** Systems level process flow diagram describing the production of energy from hydrochar. The first step of this process is hydrothermal carbonization, which involves process heating (1) and feedstock transformation (2). The second step of this process is electricity generation via hydrochar combustion, which involves gravity drainage (3) and recovered solids drying (4) and combustion (5).

**Table 5**  
Impact categories used in the impact assessment.

Impact category	Method	Abbreviation	Unit/kg
Climate change	IPCC 2007 (Forster et al., 2007)	GWP	kg CO <sub>2</sub> -eq.
Human toxicity, cancer effect <sup>a</sup>	USEtox (Rosenbaum et al., 2008)	HT-C	CTU <sub>h</sub>
Human toxicity, non-cancer effect <sup>a</sup>	USEtox (Rosenbaum et al., 2008)	HT-NC	CTU <sub>h</sub>
Photochemical ozone formation	ReCiPe midpoint (Van Zelm et al., 2008)	POF	kg NMVOC-eq.
Terrestrial acidification <sup>c</sup>	Accumulated exceedance (Seppala et al., 2006; Posch et al., 2008)	AP	AE
Terrestrial eutrophication <sup>c</sup>	Accumulated exceedance (Seppala et al., 2006; Posch et al., 2008)	TEP	AE
Freshwater eutrophication	ReCiPe midpoint (Struijs et al., 2009)	FEP	kg P-eq.
Marine eutrophication	ReCiPe midpoint (Struijs et al., 2009)	MEP	kg N-eq.
Freshwater ecotoxicity <sup>b</sup>	USEtox (Rosenbaum et al., 2008)	ET	CTU <sub>e</sub>

<sup>a</sup> CTU<sub>h</sub>: comparative toxic unit for humans.

<sup>b</sup> CTU<sub>e</sub>: comparative toxic unit for ecosystem.

<sup>c</sup> AE: accumulated exceedance (keq).

## 2.5. Model simulations

Several model simulations were performed to identify how parameters and/or components associated with food waste carbonization and/or subsequent hydrochar combustion that are not currently known (e.g., fate of metals, fate of nutrients, electricity needs, substituted energy source) influence system environmental impact, as outlined in Table 6. These parameters represent information not routinely reported/known when describing results from and operation of the hydrothermal carbonization of different feedstocks. Carbonization parameters that are known and well defined, such as hydrochar energy content and hydrochar yield, were only varied in these simulations based on the experimental results obtained from Li et al. (2013) and simulations evaluating their individual influence were not conducted in this study.

## 3. Results and discussion

### 3.1. Base case scenario

Data associated with the hydrothermal carbonization for this base case scenario were taken from the food waste carbonization experiments reported by Li et al. (2013). The specific carbonization reaction conditions modeled in this base case represent the conditions resulting in the most energetically advantageous scenario and thus the scenario most likely to be applied for the carbonization of food wastes: reaction temperature of 275 °C, reaction time of 16 h, and an initial solids concentration of 32% (food waste only, no packaging). A summary of the carbonization and gravity drainage stages (stages 1–3, Fig. 1) associated with the modeled system is included in Tables 2 and 3. Information associated with the volume and composition (e.g., chemical oxygen demand) of

**Table 6**  
Summary of model simulations.

Simulation Name	Simulation Number	Purpose	Conditions Modified
Base Case	B	Provide a base case for subsequent scenario comparison. This base case is based on experimental data and average values found in the literature. Carbonization conditions were chosen based on energy balances conducted by Li et al. (2013).	None.
Liquid treatment	B-1	Understand how treating the liquid product from HTC influences system environmental impact.	Assume 90% of removal of each liquid-phase contaminant in the HTC liquid product.
Electricity needs and offsets	E	Conduct a series of simulations to investigate how electricity-related parameters associated with the process influence system LCA. Other conditions are equivalent to the base case.	<ul style="list-style-type: none"> <li>• Energy required for HTC</li> <li>• Energy Required for Combustion</li> <li>• Efficiency associated with electricity generation from the hydrochar</li> <li>• Type of energy substituted by electricity generation from hydrochar</li> </ul>
Fate of Metals	M-1	Investigate how changes in metal fate influence process LCA. Changes in the following metal data are investigated: Al, As, Cd, Cr, Cu, Fe, Hg, Mg, Mn, Na, Ni, Pb, Se, Sr, Ti, Zn. Other conditions are equivalent to the base case.	100% of all metals remain in the solid-phase during HTC.
	M-2		100% of all metals remain in the liquid-phase during HTC.
	M-3		100% of the Hg partitions to the gas-phase during HTC.
Fate of Nutrients	N-1	Investigate how changes in nutrient fate influence process LCA. Changes in the following nutrient data are investigated: N, P, K, S. Other conditions are equivalent to the base case.	100% of all nutrients remain in the solid-phase during HTC.
	N-2		100% of all nutrients remain in the liquid-phase during HTC.
	N-3		100% of the nitrogen partitions to the gas-phase (as NH <sub>3</sub> ) during HTC.
Carbonization Conditions	C-1	Investigate how the presence of packaging materials influences system environmental impact. Note that the distribution of metals and nutrients remain the same as the base case.	<ul style="list-style-type: none"> <li>• Reaction Temperature: 250°C</li> <li>• Reaction Time: 16 hours</li> <li>• % of Packaging Materials: 0</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-2		<ul style="list-style-type: none"> <li>• Reaction Temperature: 250°C</li> <li>• Reaction Time: 16 hours</li> <li>• % of Packaging Materials: 10</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-3		<ul style="list-style-type: none"> <li>• Reaction Temperature: 250°C</li> <li>• Reaction Time: 16 hours</li> <li>• % of Packaging Materials: 40</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-4		<ul style="list-style-type: none"> <li>• Reaction Temperature: 225°C</li> <li>• Reaction Time: 16 hours</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-5		<ul style="list-style-type: none"> <li>• Reaction Temperature: 250°C</li> <li>• Reaction Time: 16 hours</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-6	Investigate how the changes in reaction temperature influence system environmental impact. Note that the distribution of metals and nutrients remain the same as the base case.	<ul style="list-style-type: none"> <li>• Reaction Temperature: 275°C</li> <li>• Reaction Time: 16 hours</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-7		<ul style="list-style-type: none"> <li>• Reaction Temperature: 275°C</li> <li>• Reaction Time: 4 hours</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-8		<ul style="list-style-type: none"> <li>• Reaction Temperature: 275°C</li> <li>• Reaction Time: 16 hours</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>
	C-9		<ul style="list-style-type: none"> <li>• Reaction Temperature: 275°C</li> <li>• Reaction Time: 96 hours</li> <li>• Electricity requirements for HTC and hydrochar combustion</li> <li>• Hydrochar yields</li> <li>• Energy, carbon, nitrogen, moisture, and VS distribution</li> </ul>

the liquid requiring treatment and the remaining moisture found in the solids following gravity drainage were also taken from the experimental results described by Li et al. (2013) and are summarized in Tables 2 and 3. Hydrochar combustion is used to generate electricity, with no heat recovery, because this is common practice in the US. In this simulation, electricity generation via hydrochar combustion was used to substitute electricity generated from coal because hydrochar is a coal-like material and will likely be combusted in coal-fired power plants. Lignite coal was specifically chosen because it has been reported that the hydrochar closely resembles the structure of this coal type (e.g., Berge et al., 2011; Libra et al., 2011).

Results from this analysis are presented in Fig. 2 and Table 7. Fig. 2 presents the percent contributions of hydrochar combustion, the HTC electricity requirements for heating, and gas and liquid emissions from carbonization associated with the base case scenario on each individual impact category, and Table 7 presents the corresponding impact potentials. The percent contribution of each of these processes is based on its individual contribution to

the impact potential. Results from this analysis indicate that hydrochar combustion (step 5) and liquid-phase emissions from HTC represent the processes that contribute most significantly to overall system environmental impact. The majority of the GWP (–99%), AP (–93%), TEP (99%), and POF (96%) impact potentials are attributed to hydrochar combustion. The energy offsets associated with the electricity generation from combusting hydrochar represent an environmental savings, as reflected in the GWP (–99%), AP (–93%), and HT-NC (–38%) impact potentials, and highlights the environmental importance associated with this component of the process when substituting electricity generated from lignite coal combustion.

In this base case scenario, the HTC liquid-phase emissions contribute most significantly (>60%) to the HT-C, HT-NC, ET, FEP and MEP impact potentials. The pollutants exerting the largest fraction of the HT-C, HT-NC, and ET impact potentials are liquid-phase metals emitted to surface water, specifically chromium, arsenic, copper, and mercury. Liquid-phase nutrient emissions to the surface water comprise the largest fraction of the FEP and MEP impact

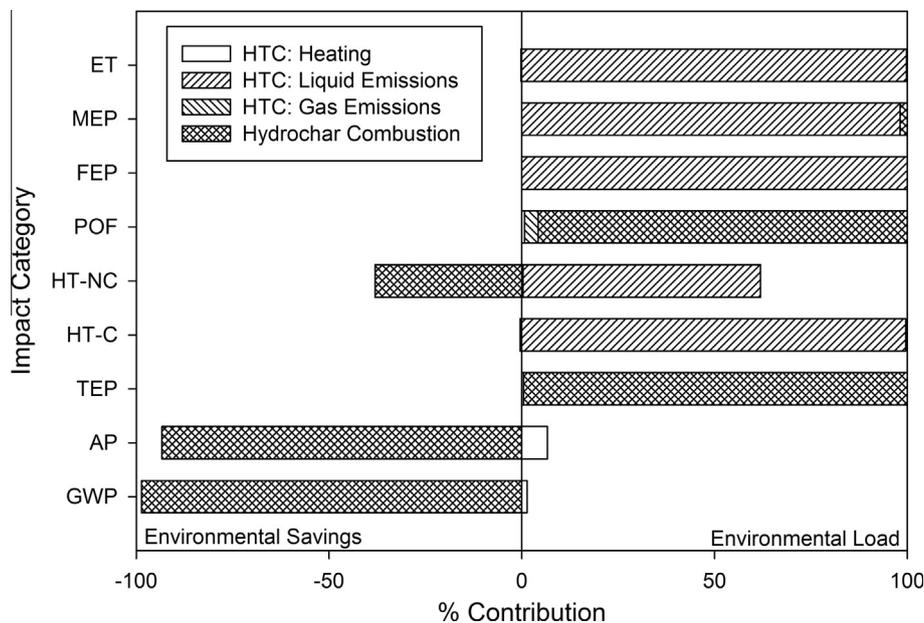


Fig. 2. Contributions associated with process components on each impact category for the base case scenario. Impact category abbreviations are defined in Table 5 and Section 2.4.

Table 7  
Impact potentials associated with the LCA scenarios.

Simulation number	GWP (kg CO <sub>2</sub> -eq./kg waste)	AP (AE/kg waste)	TEP (AE/kg waste)	HT-C (CTU <sub>h</sub> /kg waste)	HT-NC (CTU <sub>h</sub> /kg waste)	POF (kg NMVOC-eq./kg waste)	FEP (kg P-eq./kg waste)	MEP (kg N-eq./kg waste)	ET (CTU <sub>e</sub> /kg waste)
B	-1.82E-2	-3.11E-5	6.04E-4	1.45E-09	3.46E-10	1.38E-4	5.53E-4	2.92E-3	3.30E-2
B-1	-1.82E-2	-3.11E-5	6.04E-4	1.40E-10	-4.57E-10	1.38E-4	5.53E-5	3.41E-4	3.24E-3
M-1	-1.82E-2	-3.11E-5	6.04E-4	-6.36E-12	-5.45E-10	1.38E-4	5.53E-4	2.92E-3	-6.94E-5
M-2	-1.82E-2	-3.11E-5	6.04E-4	2.17E-09	1.37E-08	1.38E-4	5.53E-4	2.92E-3	4.61E-1
M-3	-1.82E-2	-3.11E-5	6.04E-4	1.50E-09	4.49E-09	1.38E-4	5.53E-4	2.92E-3	3.30E-2
N-1	-1.82E-2	-3.11E-5	6.04E-4	1.45E-09	3.46E-10	1.38E-4	3.94E-10	5.48E-5	3.30E-2
N-2	-1.82E-2	-3.11E-5	6.04E-4	1.45E-09	3.46E-10	1.38E-4	1.14E-3	1.07E-2	3.30E-2
N-3	-1.82E-2	3.90E-2	1.75E-1	1.45E-09	3.46E-10	1.38E-4	5.53E-4	1.24E-3	3.30E-2
C-1	-2.12E-2	-3.72E-5	7.02E-4	1.45E-09	4.12E-09	1.56E-4	5.53E-4	8.84E-4	1.49E-1
C-2	3.26E-2	-3.69E-5	7.02E-4	2.98E-09	4.46E-09	1.56E-4	4.98E-4	8.98E-5	1.80E-1
C-3	1.9E-1	-4.27E-5	8.43E-4	-8.99E-12	-7.75E-10	1.88E-4	5.49E-10	7.65E-5	-9.41E-5
C-4	-1.98E-2	-3.32E-5	6.61E-4	1.45E-09	2.94E-10	1.47E-4	5.53E-4	2.34E-3	3.30E-2
C-5	-2.13E-2	-3.72E-5	7.02E-4	1.45E-09	2.49E-10	1.56E-4	5.53E-4	8.84E-4	3.30E-2
C-6	-1.82E-2	-3.11E-5	6.04E-4	1.45E-09	3.46E-10	1.38E-4	5.53E-4	2.92E-3	3.30E-2
C-7	-1.89E-2	-3.16E-5	6.31E-4	1.45E-09	3.23E-10	1.41E-4	5.53E-4	2.00E-3	3.30E-2
C-8	-2.13E-2	-3.72E-5	7.02E-4	1.45E-09	2.49E-10	1.56E-4	5.53E-4	8.84E-4	3.30E-2
C-9	-1.64E-2	-2.78E-5	5.48E-4	1.46E-09	4.01E-10	1.30E-4	5.53E-4	3.64E-3	3.30E-2

potentials. Although not included in this work, treatment of the HTC liquid prior to discharge will be required to meet regulatory discharge limits. If 90% of all the liquid-phase contaminants are removed prior to discharge, the magnitude of these impact potentials decreases significantly (Table 7, simulation B-1). The HT-NC category is most affected by liquid-phase treatment; when the liquid is treated prior to discharge, the contribution of the liquid-phase emissions to the HT-NC impact category is reduced from 61% to 14%. Because of the reduction in liquid-phase emissions, the offsets associated with hydrochar combustion predominate and this category ultimately results in an environmental savings. It is important to note, however, that emissions associated with the liquid treatment process will also contribute to system environmental impact. Hong et al. (2010) report that leachate treatment contributes a small amount to system environmental impact (e.g., landfilling of waste), suggesting the impact associated with the treatment of this process water may be small. One possible treatment technique is anaerobic digestion. Wirth and Mumme (2013) report that anaerobic digestion of the process water resulting from the carbonization of corn silage results in chemical oxygen demand removal efficiency of 80% during the first phase of operation. More studies associated with anaerobic digestion, as well as other treatment processes, is needed.

Gas emissions resulting from HTC represent only a small contribution to the environmental impact associated with this base case scenario, contributing to only 3.5% and 0.01% of the POF and ET impact categories, respectively. This result is not surprising, as the gas-phase modeled does not contain compounds of significant environmental concern (Table 2). In this scenario, the carbon dioxide in the gas product does not contribute to the GWP category because all of the emitted carbon is of biogenic origin; biogenic carbon is considered neutral in this study. It should be noted, however, that more extensive evaluation of gas-phase composition is needed. Although no compounds of environmental concern were included in this scenario, there is a general lack of gas-phase data in the current body of HTC literature. Few studies report gas-phase compositions. Berge et al. (2011) report furan was detected in the gas-phase when carbonizing solid waste materials. However, specific concentrations were not measured/reported.

The HTC process itself (e.g., heating for the waste conversion, stage 1 in Fig. 1) appears to represent a fairly negligible impact on the system. This result should be interpreted and used with

caution, as this may be an artifact of a lack of data. In this scenario, the environmental impact associated with the HTC process only takes into account the electricity requirements associated with process heating. It is likely that as this process is scaled-up, the system will likely require additional equipment requiring diesel oil or possibly chemical additions for dewatering (or other processes). These items will likely affect process environmental impact, although the magnitude of this impact is unknown at this time.

### 3.2. Influence of system electricity requirements

Simulations were conducted to assess how changes in the electricity-related parameters associated with the system influence environmental impact. Electricity-related parameters were varied (Tables 4 and 6) and sensitivity ratios (SRs, defined as the percent change of the result divided by the percent change of the parameter) were subsequently calculated to quantify the effect parameter changes have on each impact category. Results from this analysis are illustrated in Fig. 3 and indicate that changes in the HTC electricity requirement for system heating impart the smallest influence on all impact categories, with SRs less than 0.02 for each category, except AP. This result is not surprising, as heating of the HTC process was found to impart the smallest contribution to each of the impact categories (Fig. 2). This result also indicates that the environmental impact due to increased energy requirements because of process heat losses during large-scale carbonization may be minimal.

Results indicate that the GWP impact category is most sensitive to changes in the electricity requirements for hydrochar drying and combustion (SR of 5.87). This impact category is also sensitive to the efficiency associated with electricity generation from hydrochar combustion (SR of 1.23). These results are not surprising, as the majority of the GWP category is attributed to hydrochar combustion. These results also highlight the need for a greater understanding associated with hydrochar combustion properties, such as ignition temperature, associated process requirements (e.g., chemical additions, equipment), and emissions (e.g., gas, ash, wastewater).

The AP impact category is most sensitive to the changes in the efficiency associated with electricity generation from combusting hydrochar. At an electricity generation efficiency < 20%, the emission offsets gained from electricity generation from hydrochar

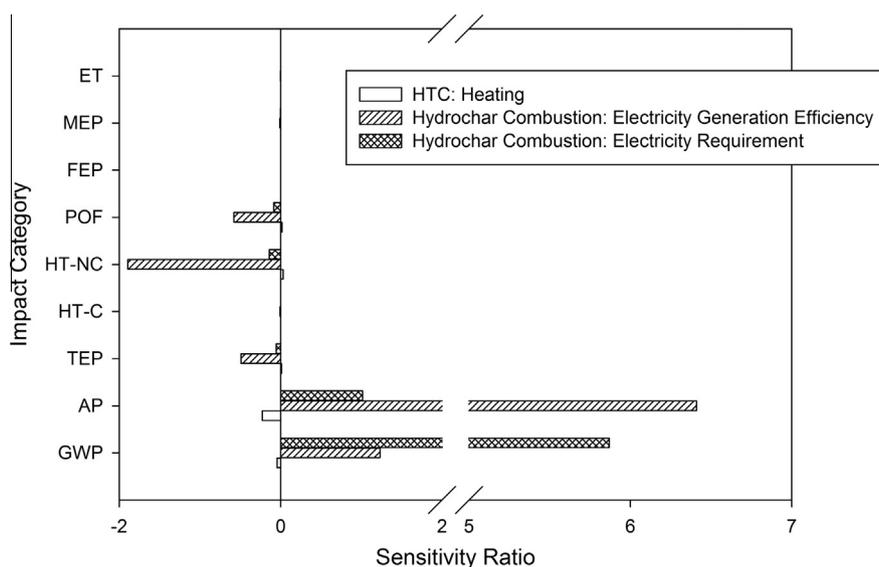


Fig. 3. Sensitivity ratios associated with changing electricity-related parameters.

combustion are no longer significant enough to cancel out emissions associated with combustion process emissions and liquid-phase emissions. Changes in the amount of electricity required for hydrochar combustion also imparts an influence on this impact potential.

The electricity generation efficiency associated with hydrochar combustion also influences the HT-NC category. As the efficiency increases, the overall HT-NC impact potential decreases. At efficiencies greater than 50%, the emission offsets obtained from electricity generation from hydrochar combustion become more significant than the liquid emissions from HTC. Although an efficiency of 50% is unlikely for traditional incineration processes, achieving greater emission offsets and thus reducing environmental impact may be achieved if heat from the combustion process is also recovered and subsequently used.

3.3. Influence of substituted energy source

Simulations were also conducted to evaluate how system environmental impact is influenced when the electricity generated from hydrochar combustion is used to offset (e.g., provide environmental credits) electricity produced from different coals (e.g., bituminous and anthracite), biomass, and the average US electricity mix. Fig. 4 illustrates, as a percent change relative to the base case (e.g., offsetting electricity generated via lignite coal), how system environmental impact is influenced when the electricity generated from hydrochar combustion offsets that generated from these alternative energy sources. A positive change in Fig. 4 indicates a relative increase in the environmental load, while a negative change indicates a relative reduction in environmental impact.

Table 8 also summarizes results from these simulations. In this table, all evaluated substituted electricity sources (e.g., coals, biomass, and US average mix) are ranked in order from least to greatest environmental impact for each category.

Substituting the electricity generated from lignite coal with that produced from hydrochar combustion results in an environmental savings for a greater number of impact categories than when offsetting the electricity generated from bituminous and anthracite coal. Of the coals evaluated, offsetting the electricity generated from lignite results in the lowest GWP, TEP, and POF impact categories, but imparts a larger impact in the AP and FEP categories. Results from this analysis also indicate that the type of coal-derived electricity offset has little to no effect on the HT-C, MEP, and ET impact categories. Substituting hydrochar-derived electricity for any coal-derived electricity results in an environmental savings for the GWP and AP impact categories (Table 8). Substituting the use of lignite and anthracite coals with electricity generated via hydrochar combustion result in the greatest positive impact on the environment because there are greater emissions associated coal-based electricity than with hydrochar combustion.

Relative to that observed in the base case, substituting the electricity generated from hydrochar combustion for that produced from biomass (e.g., gasification of poplar trees) results in a significantly greater load to the environment in the GWP, AP, and HT-NC impact categories. Lower impacts are observed for the POF and FEP impact categories. The increased load to the environment results because there are greater emissions associated with hydrochar combustion than those associated with biomass gasification, ultimately reducing the magnitude of the environmental savings associated with the electricity produced from hydrochar combustion.

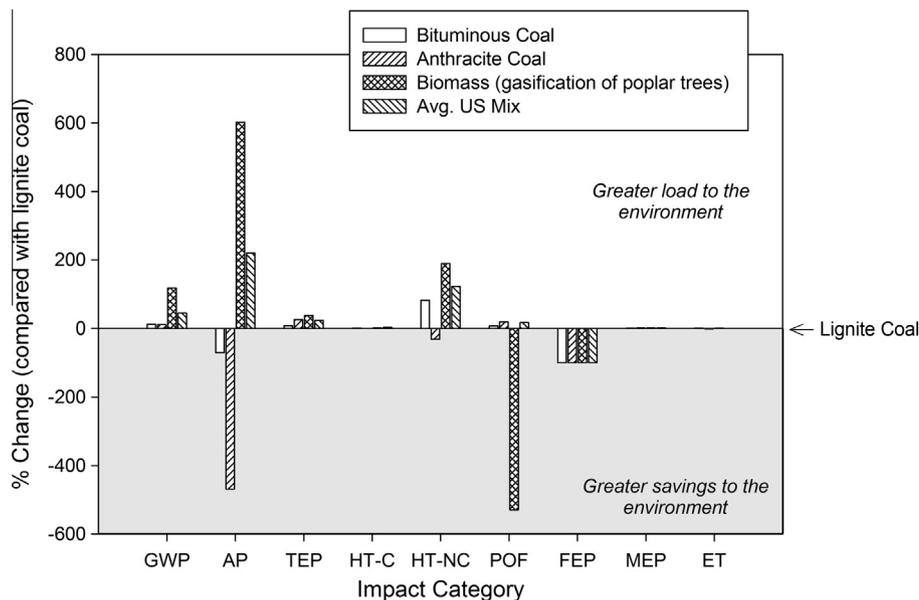


Fig. 4. The influence of the source of electricity being offset by the electricity generated from hydrochar combustion. These percent changes are presented in relation to the base case, where electricity generated from hydrochar combustion offsets that generated by lignite coal.

Table 8 Impact of offsetting different energy sources with that of electricity generated via hydrochar combustion.<sup>a</sup>

Order of Env impact		GWP	AP	TEP	HT-C	HT-NC	POF	FEP	MEP	ET
Least	1	L (-)	A (-)	L (+)	A (+)	A (+)	Bio (-)	US (+)	L (+)	A (+)
	2	A (-)	Bit (-)	Bit (+)	L (+)	L (+)	L (+)	Bio (+)	Bit (+)	US (+)
	3	Bit (-)	L (-)	US (+)	Bit (+)	Bit (+)	Bit (+)	Bit (+)	US (+)	L (+)
	4	US (-)	US (+)	A (+)	Bio (+)	US (+)	US (+)	A (+)	A (+)	Bit (+)
Greatest	5	Bio (+)	Bio (+)	Bio (+)	US (+)	Bio (+)	A (+)	L (+)	Bio (+)	Bio (+)

L = lignite coal; A = anthracite coal; Bit = bituminous coal; Bio = biomass; US = average US electricity mix.

<sup>a</sup> The notation in parentheses indicates whether the contribution associated with the energy source is positive or negative.

Biomass is ranked last (greatest impact to the environment) for 6 of the 9 impact categories (Table 8), suggesting that generating electricity from hydrochar should not be implemented if it will be used to replace biomass-derived electricity.

Similar to that observed with biomass, if the electricity generated via hydrochar combustion is used to offset the average US electricity mix, a greater load to the environment than that observed when offsetting lignite (or any other coal-like material) results for all impact categories except for FEP and ET. The overall GWP impact, however, remains negative ( $-0.0101$ ), indicating credits associated with using the electricity generated via hydrochar combustion still result in an environmental savings. No other impact category results in an environmental savings. The decision to substitute the average US electricity mix with hydrochar-derived electricity will likely depend on specific environmental priorities.

### 3.4. Fate of metals

Simulations to assess how changes in metal fate influence system environmental impact were also conducted. Little is currently known about the fate of metals during HTC. The fate of metals during HTC depends on many factors, including reaction time and temperature, process water pH, and feedstock properties. Simulations were conducted to evaluate environmental impact of two extreme cases: (1) when all metals remain integrated within the hydrochar following carbonization and (2) when all metals partition to the liquid-phase during carbonization. All other parameters/conditions modeled in the base case scenario are retained in these simulations.

Results from this analysis indicate that changes in metal fate only impart an influence on the HT-C, HT-NC, and ET impact categories (Table 7). When 100% of the metals remain integrated within the solid material following carbonization, an overall reduction in the impact associated with these categories is observed. This result is an artifact of the system boundary. In this scenario, the metals remain bound in the hydrochar and enter the hydrochar combustion facility. During combustion, the majority of the metals partition into the ash or wastewater.

When 100% of the metals partition to the liquid phase, the magnitudes of the HT-C, HT-NC, and ET categories increase, imparting a more significant load to the environment (Table 7). This result is not surprising, since there is no removal of these metals prior to discharge to the surface water. The five metals imparting the greatest influence on each of these impact categories are outlined in Table 9. This influence is impacted by both the impact method characterization factor and mass of each metal present. The characterization factors are listed in Table 9 and represent the mass

**Table 9**  
Metals imparting the greatest influence on affected impact categories.

Impact category	Metal	Impact	Characterization factor
HT-C (CTU <sub>h</sub> )	1. Chromium	2.1E-09	0.0106
	2. Arsenic	3.1E-11	0.00031
	3. Nickel	7.6E-12	0.000038
	4. Mercury	6E-13	0.00012
	5. Cadmium	1.6E-13	0.0000016
HT-NC (CTU <sub>h</sub> )	1. Zinc	1.1E-08	0.0013
	2. Arsenic	2.7E-09	0.027
	3. Mercury	7.14E-11	0.0142
	4. Cadmium	4.3E-11	0.00024
	5. Lead	2.4E-11	0.00012
ET (CTU <sub>e</sub> )	1. Zinc	0.342	39,000
	2. Copper	0.088	55,000
	3. Chromium	0.021	105,000
	4. Arsenic	0.004	40,000
	5. Nickel	0.003	15,000

normalized impact. Results from this analysis indicate that chromium and arsenic impart the greatest mass normalized impact to the HT-C category, arsenic and mercury impart the greatest mass normalized impact to the HT-NC category, and chromium and copper impart the greatest mass normalized impact to the ET category. Greater exploration associated with the fate of these metals is warranted, especially when carbonizing wastes containing larger initial masses of metals.

An additional simulation focusing on mercury fate was conducted. Mercury is the metal present in the food waste with the lowest boiling point. A scenario in which all the mercury partitions to the gas-phase during HTC was conducted to assess the potential impact with this scenario. Release of mercury to the gas-phase (assuming no treatment prior to discharge) results in an increase in the impact associated with the HT-NC category (Table 7). It should be noted that if mercury is detected in the gas-phase from HTC, removal of this contaminant will be required prior to discharge of the gas stream to the atmosphere. Thus, the addition of activated carbon or some other treatment technique will be required, which will also result in a load to the environment.

### 3.5. Fate of nutrients

Simulations were also conducted to evaluate how changes in nutrient fate (e.g., N, P, K, and S) influence system impact. All other parameters/conditions modeled in the base case scenario are retained in these simulations. Results from this analysis are shown in Table 7 and indicate that if the nutrients remain integrated within the hydrochar the impacts associated with the MEP and FEP categories are the lowest because the nutrients remain integrated within the solid material, resulting in the release of fewer liquid-phase nutrients. If all the nutrients partition to the liquid-phase, the MEP and FEP impact potentials increase by an order of magnitude. The nutrients in the liquid-phase that impart the greatest impact to the MEP and FEP impact categories are ammonium and phosphate, respectively. The recovery of these nutrients from the liquid-phase would reduce this impact. A simulation was also conducted to determine the impact of all the nitrogen partitioning to the gas-phase as NH<sub>3</sub>. Results indicate that the AP and TE, and MEP impact categories are significantly impacted by ammonia gas release (Table 7).

### 3.6. Influence of HTC reaction time and temperature

The influences of reaction temperature and reaction time are illustrated in Fig. 5. Process parameters varied during these simulations are limited based on information obtained from the experiments conducted by Li et al. (2013) and include electricity requirements for HTC and hydrochar combustion, and the distribution of carbon, energy, solids, nitrogen, moisture, and volatile solids. The fate of metals and nutrients remain the same as those associated with the base case because data associated with how their fate changes with reaction time and temperature for food wastes is unknown. All other parameters/conditions modeled in the base case scenario are retained in these simulations.

Results from this analysis indicate that there are no discernable trends associated with system environmental impact when varying reaction temperature and time, suggesting the environmental impact of the modeled system is not sensitive to changes in reaction time and temperature (e.g., electricity requirements for HTC and hydrochar combustion, and the distribution of carbon, energy, solids, nitrogen, moisture, and volatile solids). This conclusion, however, should be used with caution. The modeled energy requirements do not take into account heat losses. If heat losses occur over time, a time and temperature dependent change on system environmental impact may be observed. It is

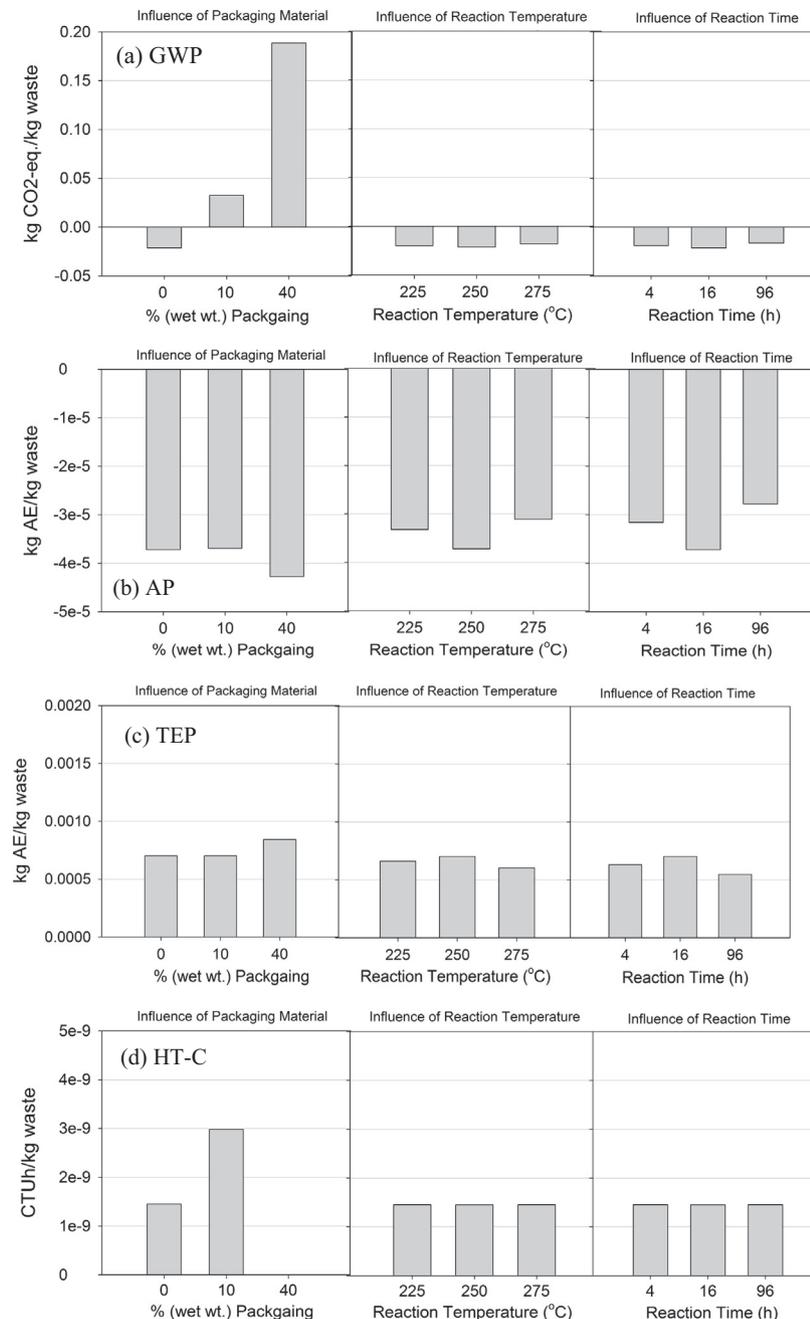


Fig. 5. Impact potentials associated with changing carbonization conditions: (a) GWP, (b) AP, (c) TEP, (d) HT-C, (e) HT-NC, (f) POF, (g) FEP, (h) MEP, and (i) ET.

expected that this impact will be small, based on results from the previously described sensitivity analysis (Fig. 2). Also, it is important to note that changes in metal and nutrient (except for nitrogen) fate is not modified as a result of changes in reaction time and temperature. Changes in the distribution of these elements will impact the LCA results. Such changes could not be incorporated in this effort because little information is currently available on how changes in feedstock and reaction conditions (e.g., reaction time and temperature) influence metal and nutrient fate.

### 3.7. Influence of packaging materials

Simulations evaluating the influence of packaging material presence on carbonization environmental impact were conducted by simulating the presence of 0%, 10%, and 40% (wt.) packaging

materials (Table 6). Packaging materials consist of 24% paper, 27% plastic and 49% cardboard (wet wt.), as described by Li et al. (2013). Data modified in these simulations are detailed in Table 6 and are limited to information obtained from the experiments conducted by Li et al. (2013), including electricity requirements for HTC and hydrochar combustion, and the distribution of carbon, energy, solids, nitrogen, moisture, and volatile solids (Tables 2 and 4). All other parameters/conditions modeled in the base case scenario are retained in these simulations.

Results are illustrated in Fig. 5 and indicate that the presence of packaging materials influences system environmental impact. The GWP impact potential (environmental load) increases as the fraction of packaging material increases. This increasing trend can be attributed to a greater mass of emissions because of a greater mass of solid material (moisture content of the feedstocks decrease with increasing packaging material fractions) and a greater mass of

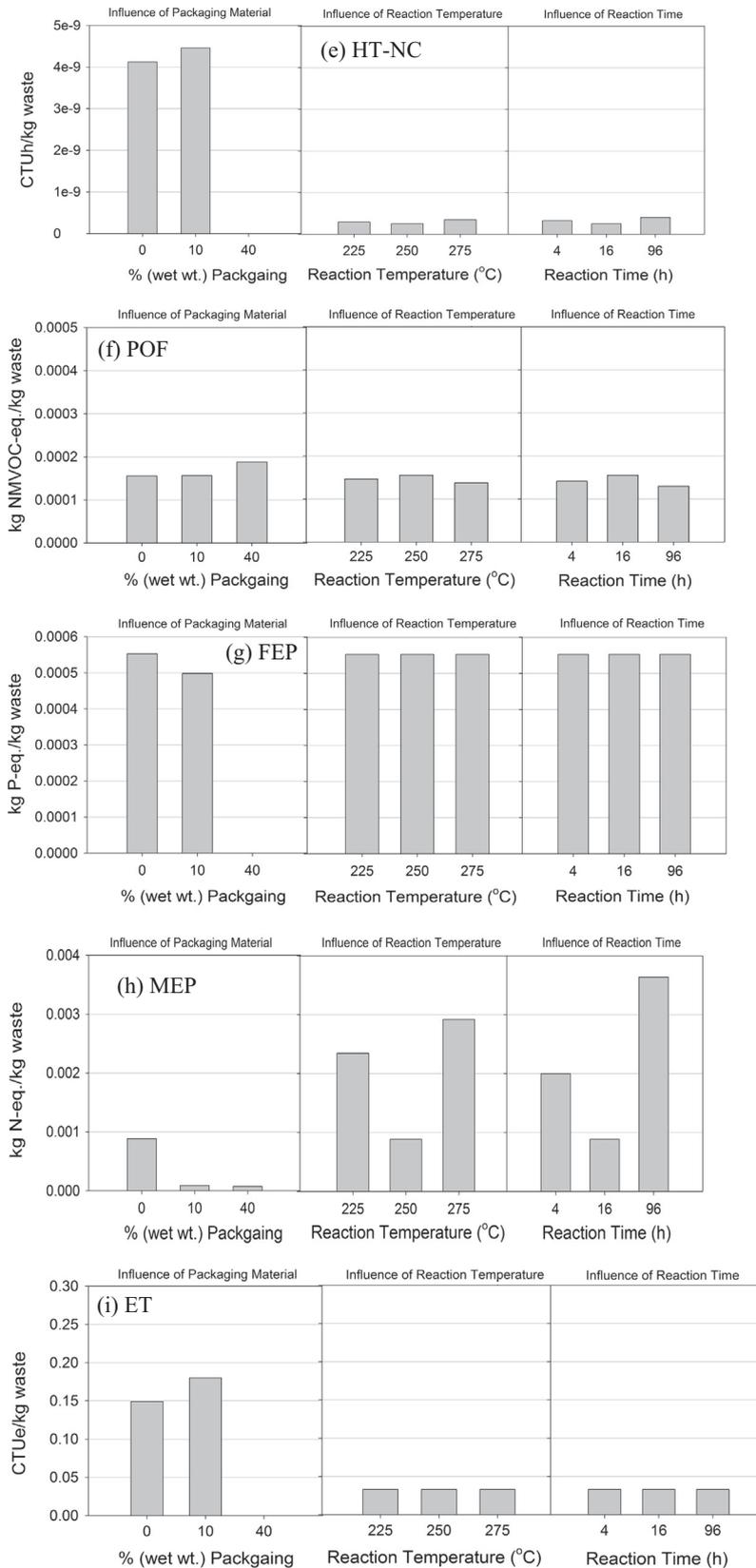


Fig. 5 (continued)

fossil-derived carbon (e.g., plastic). These results suggest that the sorting efficiency (e.g., fraction of packaging materials remaining in the food waste) will greatly influence system environmental impact, particularly the GWP.

Because there is no free drainable liquid-phase obtained when carbonizing with the largest packaging material fraction (Table 3), there are no liquid emissions and the impacts associated with the HT-C, HT-NC, FEP and ET categories are small (Fig. 5). A

significant change (lower environmental loading) in the MEP impact category is also observed when carbonizing in the presence of packaging materials. This is an artifact of nitrogen fate. A greater fraction of nitrogen remains integrated within the solid-phase when carbonizing in the presence of packaging materials. These results suggest that the environmental impact associated with the liquid-phase emissions will decrease with greater packaging materials (e.g., low sorting efficiencies).

#### 4. Implications associated with LCA results

Results from this analysis indicate that carbonization of sorted food waste followed by electricity generation from hydrochar results in a net environmental savings (negative impact) associated with the GWP for all evaluated substitution energy sources except for biomass (Table 8) and the AP for all coals evaluated (e.g., lignite, anthracite, bituminous, Table 8), illustrating the importance of and the environmental benefits associated with electricity production from hydrochar. The magnitude of the net GWP environmental impact also depends significantly on the presence of packaging materials (e.g., plastic, paper, and cardboard); as the fraction of packaging materials increases, the net GWP load to the environment also increases and is no longer an environmental savings.

Loads to the environment associated with the HT-C, HT-NC, FEP, MEP, and ET categories are most significantly attributed to the liquid emissions in the base case simulation. The impact associated with these categories will decrease if the liquid-phase is treated (each in excess of 90% removal) and/or if recoverable contaminants (e.g., metals and nutrients) in the liquid are extracted and subsequently used to offset emissions associated with their use in products (e.g., fertilizer production). It may also be possible to use this liquid stream for other purposes that add value to this liquid stream. These results highlight the need for continued investigation associated with liquid-phase treatment. If untreated, the liquid product resulting from carbonization imposes a significant environmental load; thus, its treatment merits significant study. Few studies have evaluated the feasibility of treating the liquid product using conventional processes (e.g., Wirth and Mumme, 2013). Understanding metal and nutrient removal in the liquid stream is of particular importance.

Results from this study also highlight current research gaps and the needs associated with HTC, including:

- (1) A better understanding associated with the fate of metals and nutrients during HTC is needed. There is limited information associated with the fate of these elements in the literature, but an understanding of how feedstock type and reaction conditions influence their fate is nonexistent and requires exploration.
- (2) Greater analyses to explore the composition of the liquid and gas-phase products are needed. Trace organics have been detected in the liquid and gas products. Such information is needed to understand required air pollution control devices and to conduct a more complete LCA. Furans, for example, have been detected in the gas stream from HTC (Berge et al., 2011). However, their concentration has not been reported. These compounds (because of a lack of data) were not included in this study, but will influence system impact. Evaluation of liquid-phase treatment processes is also needed.
- (3) Hydrochar combustion contributes significantly to environmental impact. Thus more studies exploring hydrochar combustion are necessary. Understanding emissions from the combustion process, as well as ignition temperatures, is necessary.

- (4) Data associated with large-scale carbonization is required for a more complete system LCA. It is unknown what equipment at such facilities will be required, as well as heat losses and the need for additional resources/chemicals (e.g., oil).

#### 5. Conclusions

A systems level analysis using EASETECH was conducted to identify the factors imparting an influence on the environmental impact of hydrochar production from carbonization of food waste and its subsequent combustion for energy generation. Results from this analysis indicate that HTC process water emissions and hydrochar combustion significantly most influence system environmental impact. The magnitude of this impact depends on the source of energy being substituted by hydrochar-generated electricity. A net environmental savings associated with the GWP and AP categories results when substituting the electricity generated via all evaluated coal types with hydrochar-generated electricity, illustrating the importance of electricity production from hydrochar particularly when it is used to offset coal-based energy sources. Decisions about using hydrochar-derived electricity to substitute the average US electricity mix need to consider specific environmental priorities.

Loads to the environment attributed to liquid-phase emissions indicate there is a significant need to develop/evaluate appropriate and environmentally beneficial management schemes for this stream. Results from this analysis also highlight a need for additional liquid and gas-phase data, an understanding of how changes in carbonization conditions (e.g., reaction time and temperature) influence metal and nutrient fate, and the exploration/feasibility of liquid-phase treatment.

This study also highlights the benefits associated with efficient sorting of food wastes from the waste stream. Results indicate that the addition of packaging influences system impact. When compared to the carbonization of pure food waste (100% sorting efficiency), the system impact increases. This increase can be attributed to a greater mass of emissions because of a greater mass of solid material and a greater mass of fossil-derived carbon (e.g., plastic) and suggest that as sorting efficiencies decrease, the load to the environment will likely increase.

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